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Soft Robotics: The Next Generation of Intelligent Machines

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Abstract

There has been an increasing interest in applying biological principles to the design and control of robots. Unlike industrial robots that are programmed to execute a rather limited number of tasks, the new generation of bio-inspired robots is expected to display a wide range of behaviours in unpredictable environments, as well as to interact safely and smoothly with human co-workers. In this article, we put forward some of the properties that will characterize these new robots: soft materials, flexible and stretchable sensors, modular and efficient actuators, self-organization and distributed control. We introduce a number of design principles; in particular, we try to comprehend the novel design space that now includes soft materials and requires a completely different way of thinking about control. We also introduce a recent case study of developing a complex humanoid robot, discuss the lessons learned and speculate about future challenges and perspectives.

1 Introduction

In the last half century, robotic technologies have had an enormous impact on industry and on society at large. For example, in the automobile manufacturing as well as in the processing of goods, a number of robotic manipulators are employed to improve the speed and efficiency of the tasks (e.g. pick-and-place). Because these robots need to move fast and accurately, they are typically designed and programmed to repeat a limited number of tasks.

More recently, there has been an increasing interest in a completely different type of robots – soft and biologically inspired robots [Albu-Schaffer *et al.*, 2008] – which can exhibit a wide range of behaviors and with which humans can co-habit and establish safe and smooth interactions [Guizzo and Ackerman, 2012], like humans do with other humans and with animals. To make this possible one has to face the challenge of dealing with the human environment, which, in contrast to the factory environment, can change very rapidly, it is very uncertain and it is often hostile [Holland and Knight, 2006]. Since the traditional methods do not scale to the new type of environments we need to identify new principles for designing and programming this new generation of robots [Pfeifer *et al.*, 2007; Pfeifer and Bongard, 2007].

In this paper we reintroduce three principles from [Pfeifer and Bongard, 2007; Pfeifer *et al.*, 2012] that we believe to be essential in addressing the current challenges in soft robotics, and analyse the novel design space in the field. The principles can be summarized as follows. The first principle postulates that active physical interaction plays a major role in inducing invariant sensor stimulation, and structuring sensory-motor information. The second principle argues for the need of self-organization mechanisms to digest and structure the information brought forward by a large number of sensor and motor elements. And the third principle notes the necessity of self-organization to be carried out by local rules. We believe that these principles will play a fundamental role in the design and construction of the new generation of bio-inspired robots.

The remainder of this paper is organized as follows. The second section discusses three relevant design principles in the context of soft robotics. The third section provides a conceptual contrast between robots designed according to biological principles and those designed according to more conventional techniques; we have called this conceptual framework "design trading space". The fourth section describes the humanoid robot we built recently in the light of our proposed design principles. The fifth section identifies a number of enabling technologies that made the construction of this robot possible in a very short time. The sixth section presents some concluding remarks.

2 Design principles

During the last decade or so, we have been exploring strategies to tackle the seemingly unsolvable challenges of placing robots in human environments. Through a number of theoretical and practical case studies with robots, we have noticed that most of these challenges are strongly related to the physical phenomena inherent to the system-environment interactions [Pfeifer *et al.*, 2007]). In this section we reintroduce some of the principles in [Pfeifer and Bongard, 2007] (and recently reformulated in [Pfeifer *et al.*, 2012]) that we consider to be particularly relevant to the new generation of soft robots.

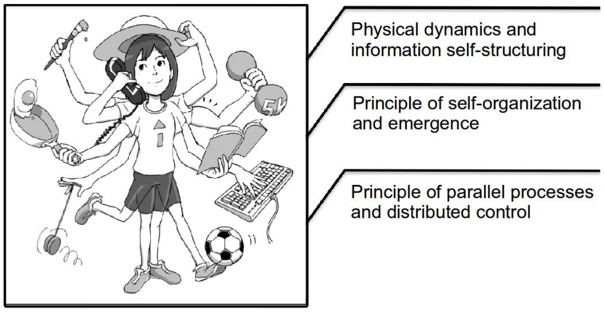

Figure 1: Principles relevant to biologically inspired soft robots: 1) active physical interaction plays a major role in inducing invariant sensor stimulation; 2) self-organization mechanisms are essential to structure sensory motor information; 3) self-organization needs to be carried out by distributed and local rules.

2.1 Principle 1: Physical dynamics and information self-structuring

When designing a robot, one of the most significant decisions is the selection and placement of the sensor and actuator elements. In manufacturing robots, all sensor and motor units are precisely selected and mounted on the robot to ensure efficient and effective completion of the tasks. As neither the tasks nor the environment are expected to change, it is not necessary to equip the robot with extra sensors, or extra motors, other than those essential to the task.

The idea that more sensors enable a robot to take into account a wider set of cues, is rather obvious and has been around for a long time. What is not so obvious is that to correctly interpret the cues provided by each sensor modality, as well as to establish coherent relations across different modalities, robots, like animals, cannot be passive receivers of information [O'Regan and Noë, 2001; Pfeifer *et al.*, 2007]. Self-propelled action plays a substantial role in inducing stereotyped patterns of spatio-temporal information, which can be used to autonomously create robust sensory-motor structures within one modality as well as across different modalities [Noë, 2004].

The importance of active exploration has been clearly shown in the pioneering study reported in [Held and Hein, 1963]. In this study it has been shown that two cats receiving the same sensory stimulation, one able to move according to its own intentions and the other being moved passively in a basket, achieve very distinct performances on subsequent visually guided tasks. The cat which was able to explore its own sensory-motor space outperformed the passive one in the basket

In *Principle 1* we postulate that sensory activity has to be exercised through active physical interactions. This idea, although rather old [Dewey, 1896], has only recently started to truly diffuse in the robotics community (see for example [Pfeifer *et al.*, 2007; Lungarella *et al.*, 2007; Olsson *et al.*, 2006]).

2.2 Principle 2: Self-organization and emergence

Mammals have millions of sensory receptors, and thousands of contractile muscle fibers, the activities of which have to be appropriately combined to obtain meaningful behaviours [Bernstein, 1967]. One way biology copes with systems of such a dimensionality is by endowing them with plastic neural mechanisms that adapt their internal information structures according to the patterns of sensory-motor stimulation experienced. When the experienced sensory-motor patterns change (for example due to body growth or injury) the system is modified to reflect these changes accordingly. To give an illustrative example, it has been demonstrated that if one connects the visual stream (from the retina photo-receptors) to the auditory cortex of a ferret, the ferret will develop neural structures in the auditory cortex which are similar to those observed in a typical visual cortex [Sharma *et al.*, 2000] (see also [Wang *et al.*, 1995]). This is an example where a neural structure which has evolved for millions of years, i.e. the auditory cortex, is shown to be completely modified when it receives different stimuli, i.e. a visual input. Thus, the new structure has not been genetically pre-programmed, but is emergent from a process of self-organization.

In robotics, once we can technically build a robot with comparable numbers of sensor and actuator elements, we will need to design methods that can structure autonomously the collected sensory-motor patterns, so that the system can cope with its high dimensionality (see for example [Weng *et al.*, 2001; Lungarella *et al.*, 2003; 2007; Asada *et al.*, 2009]). In fact, the problem of dimensionality in robotics [Sanger, 1994] (see also [Barto and Mahadevan, 2003]), like that in biology [Bernstein, 1967], is very similar to that encountered in other artificial systems that have to deal with large amounts of information, such as search engines. While the answer to this question is not trivial, it is obvious that we will not be able to control such systems by manually designing the sensory-motor relations using a simple flowchart. In *Principle 2* we postulate that the internal processing structures of a robot should be self-organized out of the experienced sensor and motor information rather than being imposed by those who program it; only then will the system be truly capable of dealing with its own dimensionality and adapt to unexpected morphological or environmental changes. In addition, whenever there are soft materials, they can no longer be directly controlled but mechanisms of self-organization have to be adopted.

2.3 Principle 3: Parallel processes and distributed control.

One of the robots built in the context of the ECCEROBOT – the ECCE2 – (a project in which our lab participated) had around 1400 cables coming out of the robot. The weight of the cables alone was comparable to that of the entire robot. Cabling, which is often regarded as a secondary activity in robotics, is one of the major barriers in the way of building more sophisticated robots.

The way mammals cope with the large bundle of sensory and motor fibres is not by bringing them all into a single place. In fact, there is no single place in the mammalian brain

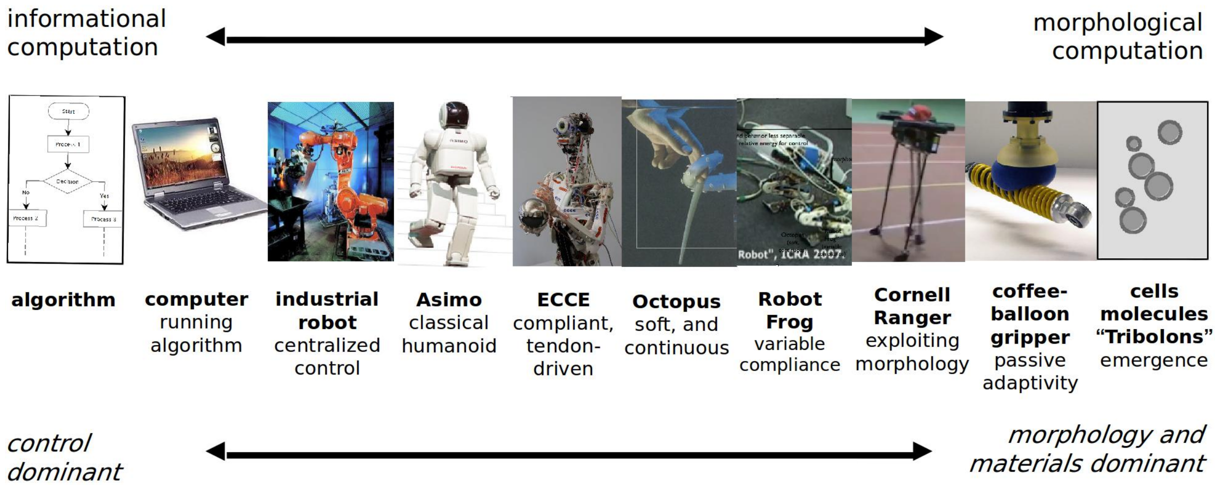

Figure 2: The design trading space. This figure illustrates the degree to which each to which each system relies on explicit control or self-organization of mechanical dynamics. On the left-hand side of the spectrum, computer algorithms and commercial computers rely on physical self-organization at the minimum level, while towards the right-hand side, more embodied, more soft, and smaller-scale systems require physical interactions as driving forces of behaviours. The design goal then is to find a proper compromise between efficiency and flexibility, taking into account that a certain level of flexibility can also be achieved by changing morphological and material characteristics.

to which all the information converges to. The central nervous system is designed in a way in which the sensor and motor information is processed in loops which feed back at different space and time scales. At the lowest levels there are, for example, reflex circuits in the spinal cord [Latash, 2008], or the magnocellular and parvocellular layers of the lateral geniculate nucleus [Bear *et al.*, 2001]. Such circuits can combine local information very rapidly, so that the sensor information that flows to and from the brain can be substantially reduced.

This kind of organization presents a number of benefits. First, it prevents all the cables to converge to a single point is space. Second, local circuits (e.g. reflexes) can respond faster to unpredictable perturbations. And, third, these loops can already combine and pre-digest a lot of sensory and motor information, which reduces significantly the data transmitted to higher-level mechanisms. Thus, in *Principle 3* we postulate that to deal with large sensor and motor patterns, processes of self-organization have to take the shape of local rules that are distributed throughout the organism.

3 Design trading space of biologically inspired soft robots

In this section, we will show that one of the most important characteristics of soft bodies is that they can incorporate some of the control or computation into their morphological and material properties, which in turn accounts for smoother and more efficient interactions with the environment [Iida and Laschi, 2011].

In Figure 2 we contrast the more conventional approaches to robotics with those created in the context of soft robots. Metaphorically speaking, there is a kind of "continuum" from computation to the physical world: On one end there is "pure" computation, the algorithm, the virtual machine; on the other, there is "molecular dynamics". The more one moves away from pure computation into the physical world, the more significant is the role played by morphology and the less direct (computational) control is possible. In most current industrial robots and humanoids like Asimo, control is centralized and there is a clear separation between the control and the controlled. As we shift from industrial robots to more compliant systems the degree of separation between control and controlled decreases, and ceases to exist as we approach the molecular level. The current challenge is then to understand what principles hold at which scales, and how we can design soft robots such that morphological elements and soft materials can be systematically used and exploited.

We start with an example from conventional robots. The state-of-the-art humanoid robots such as Asimo [Sakagami *et al.*, 2002], one of the most advanced robot in the world, have very strict requirements when it comes to the texture as well as to the steepness of the terrain they walk in. Their rigid bodies prevent them from adapting naturally to the terrain they are stepping in and require a substantial effort to accurately predict and compute the positioning of the feet.

In contrast, animals can walk over a wide range of terrains such as over sand, mud, ice, and rocks. For example, when a human walks on the beach, in spite of the irregularities of the terrain, relatively little computational effort is required to position the feet. The elasticity and compliance of the musculoskeletal system takes over at least a part of this task. Muscle-tendon complexes as well as cartilages at the joints allow allow the feet to dynamically adapt to the irregularities of the terrain and contribute significantly to keeping an upright posture.

From a soft robotics point of view, the first approach we would like to consider is the so-called exploitation of passive dynamics (see "Cornell Ranger" in Figure 2). Like Asimo, the Cornell Ranger can only walk on a very restrictive subset of grounds. However, the Cornel Ranger [Bhounsule *et al.*, 2012b; 2012a] instead of controlling every motion of the joints, is able to achieve considerably high energy efficiency by taking advantage of the passive swing of its legs during walking [Bhounsule *et al.*, 2012b; 2012a]. Strictly speaking the robot is not soft; it is made exclusively of rigid links. However, it includes one important characteristic of soft bodies, which is the ability to exploit passive properties to produce smooth interactions with the environment – at each step the passive nature of the legs, allow for energy to be partially transferred to the next step allowing it to walk smoothly and naturally.

Smooth interactions can also be found in musculoskeletal systems like the ECCEROBOT [Holland and Knight, 2006; Marques *et al.*, 2010] and other similar robots such as the Japanese Kotaro [Mizuuchi *et al.*, 2006] and Kojiro [Mizuuchi *et al.*, 2007], or the Swiss Roboy (see next section). These robots are actuated by more than 40 artificial muscles each endowed with inherent elasticity. The large number of actuators are matched by a similarly large number of proprioceptive sensors – depending on the robot, at least two or three proprioceptive sensors can be found in each muscle. Some joints are redundantly actuated, i.e. they use more muscles than those strictly necessary to move the corresponding limb parts in a given direction. These robots can distribute some basic computation to small microprocessors which are placed close to the artificial muscles, which can carry out local feedback loops involving one or two muscles (e.g. they can control the length of a muscle in closed loop). However, when compared to the mammalian spinal cord, these computations are still very rudimentary.

In terms of softness, a more extreme platform is given by the Octopus robot (see Figure 2). This robot, which tries to mimic the mechanical apparatus of an actual octopus, is entirely made of a continuum of deformable silicone materials, and can exhibit motions with infinitely many degrees of freedom [Margheri *et al.*, 2012; Mazzolai *et al.*, 2012]. A less extreme example, but still soft and continuous, can be found in the "coffee balloon gripper" (see Figure 2). This gripper can passively adapt its shape (continuously) to grasp a surprisingly wide variety of objects [Brown *et al.*, 2010].

It is important to notice that none of these case studies demonstrate any "intelligent" in a traditional sense such as solving complex and autonomous navigation problems, but they present a few fundamental challenges that need to be addressed in the next generation of robots. First, essential competences such as efficient motion control, grasping of a variety of objects, and achieving behavioural diversity, require low-level physical system-environment interactions. Once mechanical dynamics can be properly exploited, control and computation can be considerably simplified by outsourcing computation to the material properties. Second, many of these systems are developed on the basis of unconventional design strategies such as control of passive dynamics, continuous deformable bodies, or over-redundant actuation systems. And third, these case studies show the technological challenges in the future of soft robotics, which include a large number of degrees of freedom as well as a high density of sensors.

Currently, these challenges can only be addressed in a rather *ad hoc* way, to solve specific problems in our robots. For example, we place springs to increase the stability of walking robots [Pfeifer *et al.*, 2006], but we can only identify the right physical properties of the springs (e.g. elasticity and damping coefficients) by trial and error, and only after the robot is observed in action. In general this strategy works, but we need an appropriate methodology that determines the way in which morphological elements can be incorporated into a robot's body in more systematic ways.

4 Developmental robotics: Roboy, a novel research platform

In our lab we have recently built a tendon-driven humanoid robot, Roboy, that is actuated by soft artificial muscles. The goal of the project was to build a complete musculoskeletal robot, using manufacturing techniques (e.g. 3D printing) so that we can investigate the application of some of the principles mentioned above in a systematic way.

The robot incorporates a large number of degrees of freedom actuated by 48 motor units. Each motor unit consists of a module with actuation, proprioceptive sensing and low-level control electronics. The actuator consists of a rotary DC motor in series with a piece of cable and an elastic spring. When the motor is active it reels the cable and produces an analogue to a muscle contraction. On the motor side the cable is guided through a system of pulleys, one of which is attached to a spring. When force is applied to the muscle, it deforms the spring providing the overall muscle complex with intrinsic elasticity.

On the sensor side, each muscle unit contains 3 sensors: a force sensor, and two absolute encoders, one to estimate the angular position of the motor during normal operation and another to estimate the angular position of the motor as soon as the robot is switched ON. These three sensors provide information analogous to that present in the mammalian muscle. The force sensor provides a direct estimation of the force in the muscle (similar to the mammalian Golgi-tendon organ), whereas the combination of the three sensors provide the muscle with an estimation of its length (similar to the mammalian muscle spindle).

The design of Roboy attempts to address some of the principles described in Section 2 as well as some of the design principles mentioned in Section 3. First, the robot entails a large number of sensor and motor elements, which makes it a particularly challenging platform. Second, a number of self-organization strategies are currently under investigation at our lab to deal with the large dimensionality of this type of robots [Lungarella *et al.*, 2007; Marques *et al.*, 2013]. These strategies are not yet implemented in Roboy but we believe that the robot will provide an excellent platform to test them. Third, the robot has inherent elasticity, which allows it to safely interact with objects and humans. And forth, low-level control electronics allow for local and distributed feedback loops for

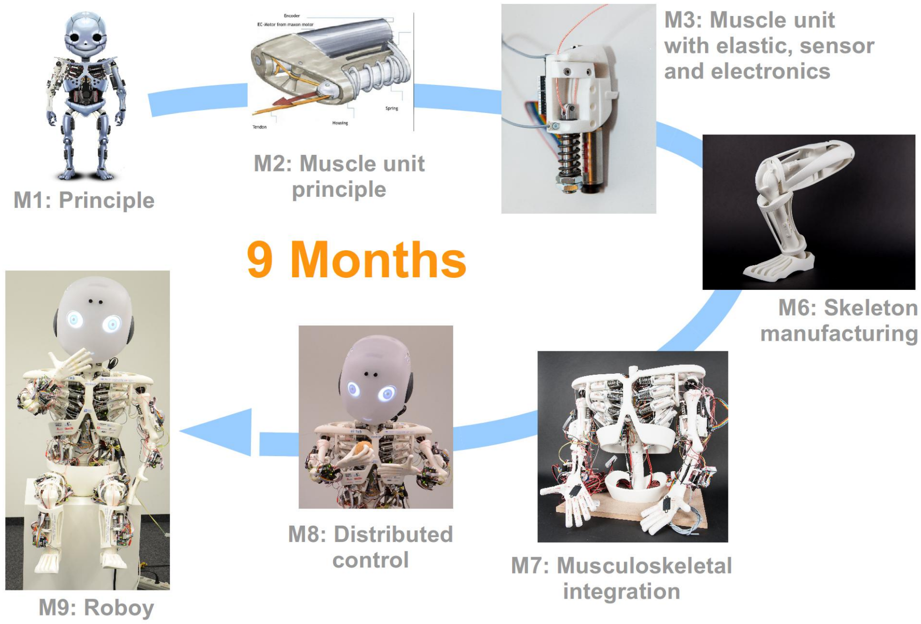

Figure 3: The Roboy Project: building a bio-inspired tendon-driven humanoid in nine months. The romantic vision of the Roboy project was motivated by the fact that in nature, a complete human body develops "from scratch" into a complete human body. Because Roboy had to be finished by the time of the anniversary celebration of our laboratory, we had severe time constraints which, of course, posed many challenges.

muscle force and muscle length control.

5 Enabling technologies and challenges

An interesting challenge of the Roboy project was the nine-month time constraint of development, which is extremely short if compared to those of other human-like robots (these robots usually require several years of development time). We have found that the success of this project was largely relying on the "soft components". For example, the entire design processes of the robot were extremely *soft* in a sense that we were not able to rigidly plan every component of the robot to the last details at the beginning. With a rough body plan of the whole robot, we had to start designing and fabricating parts while keeping them modifiable or flexibly assembled later into a coherent system. Also, the modularity and decentralization of the design, as in most animals and the other soft continuum robots, played an important role: The muscle units and their tendon-driven actuation strategy, as well as many other parts of this robot, were designed to be modular and distributed such that they could be composed of the same or similar components and structures. These characteristics are extremely important because, on the one hand, they lead to shorter development times (compared to designing every part differently), and, on the other, the parts can be more easily repaired or reassembled when unexpected changes of designs or failure of components were discovered. And finally, another *soft* aspect of this robot is the whole body structure being physically elastic, flexible and back-drivable. This property is particularly important when many components (e.g. hundreds of sensor, motor, and skeletal components) have to fit into a limited space of the body, and the assembled structures need to be safely and actively interact with humans.

We identified four enabling technologies that allowed us build Roboy in such a short time period (Figure 4). First, 3D printing provided an easy and rapid way of constructing mechanical prototypes which could be iterated until they were ready to be incorporated in the final design. Second, the clear separation of the entire design into actuator units and skeleton provided modularity in the final assembly. Third, the incorporation of actuation, elasticity, sensor inputs, and electronics into a single muscle unit reduced the cabling significantly and simplified the design and construction of the robot. And fourth, the outsourcing of computational effort to the low-level controllers in each muscle, reduced significantly the communication with the central system. At the moment, and given that most of these enabling technologies have been identified, building 10 new replicas of Roboy should require no more than two persons working for no longer than two months.

6 Conclusion

In this paper, we discussed the next generation of intelligent machines – soft machines capable of inhabiting the human environment and behave in flexible and adaptive ways. We postulated three essential principles for the design of such machines, and illustrated the benefits of outsourcing computation to soft materials and morphological properties (e.g. energy efficiency and adaptability). We closed our paper with a description of our most recent soft tendon-driven humanoid robot and the identification of a set of technologies that made

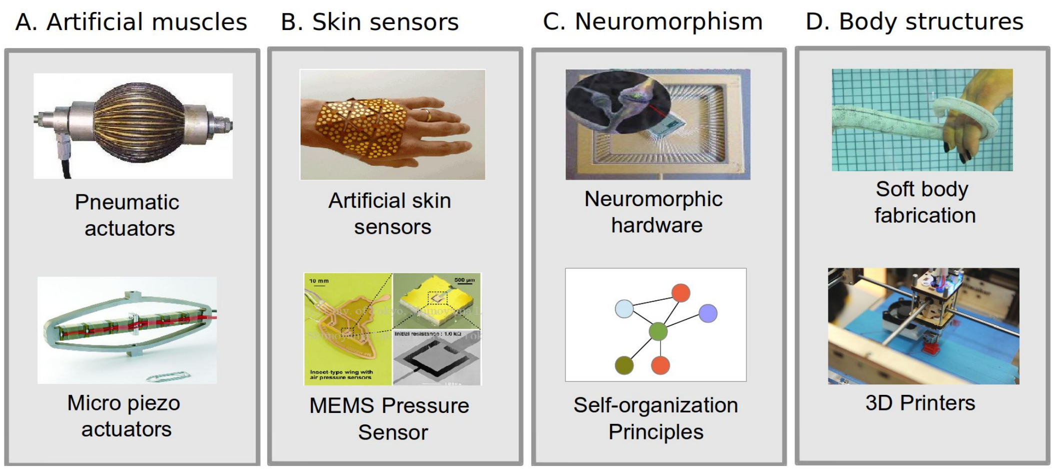

Figure 4: Examples of enabling technologies. A: Many different types of artificial muscles (such as pneumatic actuators and micro piezo actuators) have been investigated to control soft and flexible bodies. B: Sensing of continuum and soft bodies is also a challenge where new technologies such as skin sensors and MEMS components are necessary. C: Computing units become more distributed and parallelized to process many sensory and motor devices simultaneously. D: Unconventional manufacturing techniques such as soft body fabrication and 3D printing are essential to develop soft and flexible mechanical structures.

the project possible.

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